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A Publication of the Society of Economic Paleontologists and Mineralogists
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The American Association of Petroleum Geologists

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 16, NO. 1, PP. 3–13
TABLES 1–4, APRIL, 1946

A COMPARISON OF THREE SIEVE SHAKERS

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ABSTRACT

Three mechanical sieve shakers are compared with each other and with hand shaking in order to establish their relative efficiency. Four cuts of a sample of river sand are used. Phi means computed from the several size distributions are compared by the method of analysis of variance. It is demonstrated that a mechanical sieve shaker which includes a jarring action is superior to two others having horizontal motion only.

PURPOSE OF STUDY

For a short period in 1944 three widely differing sieve shakers were available to the sedimentation laboratory of the State Geological Survey of Kansas. At that time tests were made to determine whether or not there were any significant differences in mechanical analyses of a sand sample made with the three shakers.

The American Society for Testing Materials (1944, p. 442) has published specifications for sieving which include a statement that sieves should be given a "lateral and vertical motion . . . accompanied by jarring." None of the three shakers described in the present paper gives vertical motion to the sieves. The A. S. T. M. requires that "sieving shall be continued until not more than 1 per cent by weight of the residue passes any sieve during one minute," and that "when mechanical sieving is used, the thoroughness of sieving shall be tested by using the hand method of sieving as described above."

No attempt has been made in the present study to follow the methods of the A. S. T. M. in testing the completeness of sieving because standardization of one minute of hand sieving is difficult and because screens of two different diameters were used. A rough check was made, however, on the relative efficiency of hand sieving and mechanical sieving.

The error introduced by varying the type of sieve shaker is but one of a group of errors involved in mechanical analysis, many of which have been tabulated by Wentworth (1926, p. 33). These have been grouped into "field error" or sampling error and "laboratory error" (Krumbein, 1934). For purposes of this paper the laboratory error has been subdivided as follows: (1) splitting error, (2) shaker error, (3) time error, and (4) experimental error.

For most practical purposes the sampling error will greatly outweigh the laboratory error, including shaker variation. Sampling error, however, varies in magnitude with the type of deposit and method of sampling; in certain industrial and engineering problems encountered in connection with artificial materials it is small. In the present experiment only one sample was used, thus eliminating any measure of the sampling error. The limitation of the study to one sample also excludes the measurement of the effects of variation in grain size, shape, roundness, and composition.

Other causes of error listed by Wentworth that have been essentially eliminated in the present study either by double checking or by choice of technique are loss of fine grades on cloth, loss of fine grades by washing, unsound splitting method, and errors in weighing and computation. Errors in sieve-opening ratios and non-uniform sieve openings are a

possible cause of variation; a quantitative study of their effect on the resulting size distribution is beyond the scope of this paper.

Every precaution was taken to avoid the loss of material during the removal of sand from the sieves. The mean total loss per split after sixty-one analyses was only 1 per cent, or an average loss of 0.07 per cent for each analysis. Methods of cleaning the sieves were standardized and kept uniform throughout the laboratory work.

From a study of this kind one can generalize only to the sort of sample which was used here; that is, sand with essentially the same size frequency distribution. Similar data on other types of material would be required to broaden the conclusions.

DESCRIPTION OF SIEVE SHAKERS

The first sieve shaker, referred to here as Shaker 1, is used with 8-inch sieves, and reproduces the horizontal circular motion and vertical tapping given to testing-sieves in hand sieving, but with a uniform mechanical motion permitting a high degree of standardization. The shaker is operated by a $\frac{1}{4}$ horse-power electric motor operating at a speed of 1,725 r.p.m. The period of oscillation of the sieves is about 288 per minute, and the rate of tapping is about 150 per minute.

Shaker 2, used with the same set of 8-inch sieves as Shaker 1, is a gyratory type suspended from the ceiling or other support by an iron loop in the top of the frame, and oscillating from the point of suspension. There are no mechanical shocks or vertical motion. It is operated by a $\frac{1}{8}$ horse-power electric motor driving an unbalanced wheel at 900 r.p.m.

Shaker 3 is used with 3-inch sieves and provides combined horizontal oscillation and rotation. The motor is a $\frac{1}{4}$ horsepower electric motor operated at 1,750 r.p.m. The sieves oscillate at a rate of about 233 r.p.m. This shaker was built primarily as a portable machine to be used in the field, and has the advantage of compactness and light weight. In usual practice the sieves are jarred by hitting them with a hammer at frequent intervals during the mechanical shaking process. This procedure was not followed in the present study because of difficulties in standardization of the technique.

An electric time switch was used in conjunction with all three sieve shakers.

PROCEDURE

A sample of river sand collected from the vicinity of the northeast end of the Kaw River bridge at Lawrence, Kansas, was chosen for analysis because of its wide range in particle size and poor sorting, assuring the presence of a measurable amount of sand in several sieves. The sample was split into four cuts of approximately 100 grams each by means of a Jones-type sample splitter. The four splits of sand have been lettered A, B, C, and D.

Each split was screened through a series of sieves with openings of Wentworth grades from 2 mm. to .062 mm. in each sieve shaker for periods of time of 5 minutes, 10 minutes, and 60 minutes. In addition to this, each split was sieved for 60 minutes in the respective shakers followed in each case by 10 minutes by hand. The splits were also sieved for 10 minutes by hand alone. In order to determine the amount of variation caused by sieving in one shaker, a split was sieved for 5 minutes four times in each of the three shakers. The analyses are given in Table 4, and the results are expressed in terms of phi arithmetic mean (M_ϕ), phi standard deviation (σ_ϕ), and phi skewness (Sk_ϕ) in Table 1.*

The phi statistics rather than the amount of material passing through or retained on individual sieves were used as measures of sieve-shaker efficiency for several reasons. (1) They are parameters

* Pearson's formula for skewness was used: $Sk = \frac{3(M - Md)}{\sigma}$, where M = mean, Md = median, and σ = standard deviation.

commonly used by sedimentationists in describing a particle-size frequency distribution, and their values are affected by the whole distribution. (2) The quantity passing through or retained on a given sieve is an arbitrary measure, the values of which would produce widely differing and perhaps contradictory results depending upon the particular sieve chosen and the size distribution of the material tested. (3) Since the quantity retained on a sieve is determined not only by the quantity passing through it but also by the quantity passing through the coarser sieves above, the increase or decrease in weight of material on a certain sieve with increase in time cannot represent a clear-cut trend.

TABLE 1. *Values of phi mean, phi standard deviation, and phi skewness*

Split	Time	Method											
		Shaker 1			Shaker 2			Shaker 3			Hand		
		$M\phi$	$\sigma\phi$	$Sk\phi$	$M\phi$	$\sigma\phi$	$Sk\phi$	$M\phi$	$\sigma\phi$	$Sk\phi$	$M\phi$	$\sigma\phi$	$Sk\phi$
A.....	5	1.492	1.040	.297	1.438	1.029	.271	1.371	0.989	.264			
B.....	5	1.475	1.044	.287	1.422	1.029	.265	1.348	.989	.237			
C.....	5	1.466	1.041	.280	1.414	1.025	.255	1.345	.992	.224			
D.....	5	1.484	1.033	.299	1.423	1.020	.262	1.349	1.001	.210			
A.....	10	1.498	1.046	.304	1.450	1.035	.284	1.370	.996	.250	1.486	1.033	.296
B.....	10	1.484	1.045	.293	1.431	1.033	.273	1.359	.991	.248	1.470	1.029	.286
C.....	10	1.469	1.033	.276	1.425	1.031	.268	1.348	.993	.233	1.462	1.029	.277
D.....	10	1.492	1.033	.302	1.434	1.017	.274	1.359	1.002	.216	1.475	1.025	.299
A.....	60	1.524	1.048	.315	1.468	1.031	.294	1.384	1.003	.260			
B.....	60	1.507	1.048	.309	1.452	1.040	.286	1.371	1.002	.254			
C.....	60	1.499	1.049	.300	1.445	1.031	.288	1.370	.997	.235			
D.....	60	1.515	1.037	.312	1.450	1.026	.287	1.389	.992	.254			
A.....	70	1.526	1.050	.323	1.484	1.037	.298	1.463	.991	.266			
B.....	70	1.510	1.045	.307	1.471	1.040	.288	1.450	.992	.251			
C.....	70	1.500	1.040	.294	1.468	1.036	.284	1.420	.984	.213			
D.....	70	1.516	1.039	.318	1.481	1.029	.300	1.432	1.002	.216			
Repetitions with Same Split													
A.....	5				1.438	1.029	.271						
A.....	5				1.442	1.033	.279						
A.....	5				1.440	1.027	.278						
A.....	5				1.440	1.028	.280						
B.....	5	1.475	1.044	.287									
B.....	5	1.472	1.038	.286									
B.....	5	1.474	1.037	.284									
B.....	5	1.474	1.036	.284									
C.....	5							1.345	.992	.224			
C.....	5							1.342	.986	.228			
C.....	5							1.336	.990	.215			
C.....	5							1.339	0.986	.222			

STATISTICAL ANALYSIS

Comparison of phi means. The data of Table 1 form the basis of the subsequent analysis. First those values of M_ϕ which were determined for the four splits screened in the three shakers for 5, 10, and 60 minutes will be compared by the method of analysis of variance (Fisher, 1938; Snedecor, 1940). The effect of 10 minutes of hand shaking will be investigated later. Analysis of variance is the only method which provides a complete analysis of the contributions of the several factors to the total variance. It is particularly suited to the type of data at hand. The total variance of the 36 M_ϕ's can be subdivided into variance due to differences between the three shakers, variance due to differences between the three timings, variance due to differences between the four splits, and the several interaction variances. If no systematic change is introduced by the use of different shakers, different lengths of time, or different splits, then the resulting vari-

ances will not differ significantly from the error variance. The analysis for M_ϕ is presented in Table 2. The table includes the F ratios, obtained by dividing each mean square by the appropriate error mean square. The 5 per cent points and the 1 per cent points, given in the last columns of the table, are the F ratios which would be obtained 5 per cent and 1 per cent of the time by chance alone (Snedecor, 1940, pp. 184–87).

TABLE 2. *Analysis of variance of* $M\phi$

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F	5% Point	1% Point
Between shakers	2	.0998471	.0499236	F_1: 2269	5.14	10.92
Between times	2	.0053861	.0026930	F_2: 240	5.14	10.92
Between splits	3	.0026903	.0008968	F_3: 50.7	4.76	9.78
Shakers × times	4	.0000869	.0000217	1.40	3.26	5.41
Shakers × splits	6	.0001322	.0000220	1.42	3.00	4.82
Times × splits	6	.0000672	.0000112	—	3.00	4.82
Shakers × times × splits	12	.0001858	.0000155	—	—	—
Total	35	.1083956	—	—	—	—

The F ratios for the first-order interactions are computed with the second-order interaction (.0000155) as the error mean square. Owing to the nature of the experiment, the calculation of the first three F's is less simple. The selection of shakers and of timings is not a random process; the selection of splits, however, is random and could not be duplicated in a second experiment. The *shakers* × *times* interaction, therefore, should not be employed as part of the error mean square. The *between shakers* mean square is divided by the *shakers* × *splits* mean square to get F_1. F_2 is *between times* divided by *times* × *splits*. F_3 is *between splits* divided by *shakers* × *splits* plus *times* × *splits* minus *shakers* × *times* × *splits*, or $.0008968 \div (.0000220 + .0000112 - .0000155) = 50.7$, with 3 and 6 degrees of freedom. This last test is only an approximate one, for the exact distribution of F is not known for this case. The error, however, would not be large enough to alter the conclusion for the present data.*

The results of the analysis clearly indicate highly significant differences between the phi means obtained for the three shakers, between means obtained for the three sieving times, and between means obtained for the four splits of the sample of sand. The shaker means, given in Table 3, reveal that Shaker 3 differs more from Shakers 1 and 2 than the latter do from each other, although all differences between shakers are statistically significant. Shaker 1, then, is the most efficient shaker in that it yields the highest means for any given sieving time. One or more of three factors may be responsible for the failure of Shaker 3 to yield means comparable with those for the other two shakers: (1) The action may not be sufficiently violent for satisfactory screening to take place. (2) The 3-inch sieves may cause the material to pile up too much for adequate screening to occur in the time allowed. (3) Although the mesh openings of the various sieves are purported to be the same as the mesh openings of the 8-inch sieves used in

* A complete explanation of this procedure would be out of place in this paper. The writers are indebted to Prof. George W. Snedecor for suggesting its use. He treats the problem in the fourth edition of his *Statistical Methods*, in press at this writing.

Shakers 1 and 2, slight differences might exist between corresponding sieves.

With regard to the significant differences between the results for the various lengths of time, one finds greater increases for all shakers and for all splits when the time is increased from 10 to 60 minutes than when it is increased from 5 to 10 minutes. The rate of increase from 5 to 10 minutes, .0016 per minute, however, is greater than the rate of increase from 10 to 60 minutes, .0004 per minute. The corresponding rates of increase computed for each shaker differ but slightly from those computed for the combined data. Thus, increasing the length of time of sieving produces diminishing returns, a result which has been demonstrated previously by Wentworth (1927).

TABLE 3. *Mean values of Mϕ for sieve shakers, timings, and splits*

Subclass	Number of Observations Averaged	Mean $M\phi$
Sieve shakers:		
1	12	1.492
2	12	1.438
3	12	1.364
Times:		
5 minutes	12	1.419
10 minutes	12	1.427
60 minutes	12	1.448
Splits:		
A	9	1.444
B	9	1.428
C	9	1.420
D	9	1.433

It was suggested earlier in this report that part of the variance may be due to loss of material and to breakage and wear of grains. There is no evidence, however, that the loss of material was other than random among the seven size-groups. For example, if the finest grade were the most likely to blow away during the handling of the sieves, then, other things being equal, the means would tend to get smaller. At the bottom of Table 1 results are given for four 5-minute runs each of Splits A, B, and C in Shakers 2, 1, and 3, respectively. In no instance is there a trend among the means.

In order to learn the extent to which there might be breakage and wear of grains during the total time a sample was analyzed in one shaker, three additional analyses have been made, which are not included in Table 1. Sample A has been run three times through Shaker 1, the only shaker employing jarring action, for periods of 10 minutes, 145 minutes, and 10 minutes. The middle period represents the total time a sample was in one shaker during the experiment. The loss of material amounted to 0.26 grams, or 0.23 per cent, a figure comparable with that reported for the experiment as a whole. The mean (1.501) for the second 10-minute period exceeds the mean (1.495) for the first 10-minute period by only .006, which might easily be attributable to chance. If some wear does take place, it is not in such an amount as to account for the differences noted between times (nor those between shakers). Inasmuch as each split in the experiment was sieved for 60 minutes first, then for 10 minutes, and finally for 5 minutes in each shaker, the only possible effect of wear would have been to minimize the "times" differences.

The significant differences between the splits, although not nearly so large as those for shakers and somewhat smaller than those for times, attest to the sensitivity of the sieve shakers. Splits obtained by the method used in this study are considered satisfactory for most practical work (Wentworth, 1927). The range of the values for the splits, given in Table 3, is only .024. The range of the splits' means for Shaker 1 is .027, for Shaker 2: .024, and for Shaker 3: .021. These figures, although unimportant of themselves due to their similarity, corroborate our earlier finding that Shaker 1 is the most efficient, for it appears most likely to reveal small distinctions between

splits. By the same reasoning, Shaker 3 appears to be least discriminative.

The first-order interaction variances are not statistically significant. The *F* ratios all fall below the 5 per cent level. Thus the variations in time effect changes of about the same order in different shakers and for different splits. Likewise, the differences between the shakers are reasonably uniform for the four splits.

The data at the bottom of Table 1 afford a means of testing the consistency of results for any shaker. In order to eliminate differences due to shakers and those due to splits the variance between means within the three groups has been computed. The sum of squares is .0000577 with 9 degrees of freedom (3 d.f. within each of three groups). The mean square, therefore, is .0000064, smaller than the triple interaction variance for the complete analysis of Table 2. The two estimates, however, do not differ significantly; hence the 5-minute analyses tend to verify the estimate of experimental error furnished by the triple interaction. This result shows that the second-order interaction probably contains no component other than error. There is no reason to believe that the 10- and 60-minute analyses are not equally repeatable.

Hand sieving. Inasmuch as the A. S. T. M. evaluates the efficiency of mechanical sieve shakers by comparison with hand sieving, each of the four splits was sieved for 10 minutes in the 8-inch sieves by hand, and the resulting means, standard deviations, and skewness measures were computed (see Table 1). Qualitative comparison indicates that the phi means are approximately the same as those obtained by 5 or 10 minutes in Shaker 1, are slightly higher than those for 60 minutes in Shaker 2, and definitely higher than those for 60 minutes in Shaker 3.

To test the relative completeness of screening after 60 minutes in each sieve shaker, each split was sieved for an hour in each shaker and subsequently for 10 minutes by hand. The results are expressed in the "70 minutes" rows of Table 1. Examination of the phi-mean values shows that a period of 10 minutes of hand sieving following 60 minutes in Shaker 1 effects no appreciable increase in phi mean. For Shaker 3 the increase is greater, but the values are about the same order of magnitude as those obtained by hand sieving alone. The increase in mean is most pronounced in Shaker 3. An increase of this magnitude indicates that the movement of the shaker is less severe than that of the other shakers. The smaller means for 70 minutes in Shaker 3, compared with the 10-minute hand-sieving values for 8-inch sieves, substantiate an earlier observation that the small diameter of the sieves causes overloading which tends to prevent particles from passing through.

Comparison of phi standard deviations and phi skewness values. Table 1 shows that increasing the length of time that the sand is sieved in any one shaker appears not materially to affect the values of the standard deviation and skewness. This finding is in harmony with that of Otto and Levet (1940). The sigmas and skewness measures for Shaker 2 are slightly lower than those for Shaker 1, and those for Shaker 3 are definitely lower than the others. The larger standard deviations obtained by the sieve shakers which have been shown to be more efficient result from more effective screening in the smaller particle sizes. The greater efficiency of Shakers 1 and 2 in screening the smaller sizes also accounts for the greater positive skewness in the size distributions determined by these two sieve shakers.

SUMMARY OF CONCLUSIONS

For sand similar to the sample which was subjected to analysis, the following conclusions may be listed:

1. Shaker 1 is more efficient than either Shaker 2 or Shaker 3. Specifically, Shaker 1 gives results in a 5-minute period which are not quite equalled either by hand shaking or by the other

shakers for any time period used in this investigation. Its superiority is probably due to the tapping which only this shaker received. The relative thoroughness of the sieving is demonstrated not only by the larger phi means but also by somewhat larger phi standard deviations and phi skewness measures.

2. Shaker 3 is the least efficient sieve shaker. It may give more satisfactory results, however, with different material from that employed in the present experiment. Evidence has been presented which indicates that the small sieves may hamper the sieving process. It should be investigated further with a smaller sample in order that a large amount of material can not accumulate on any one sieve and so hinder the separation.

3. A period of 5 minutes for Shaker 1 yields statistics comparable with those for 10 minutes of hand sieving. An hour in Shaker 2 is somewhat less effective than the 10-minute hand sieving. These comparisons involve the same 8-inch sieves.

4. The small amount of loss of material during its handling for the several analyses appears to introduce no bias in the resulting parameters.

5. It is unlikely that even the period of two hours, twenty-five minutes, during which a split was subjected to the action of one shaker produced a measurable degree of wear or breakage of sand grains.

6. In general, a longer period of shaking gives higher phi means than a shorter period by any method.

7. Statistically significant differences were found between the splits derived from the sample by means of a Jones-type sample splitter. The actual differences, however, are very small.

8. In order of magnitude the differences between shakers are greatest, those between sieving times next largest, and those between splits smallest.

IMPLICATIONS OF THE EXPERIMENT

The results of this experiment, within the limitations of the sediment involved, suggest the following implications:

1. Results based on one type of sieve shaker are not exactly comparable with those based on a different type of sieve shaker. Information concerning the shaker used for an analysis should be included in research reports.

2. Any one of the three sieve shakers under discussion is sufficiently sensitive to slight variations in the composition of the sediment that it can be used for comparative purposes.

3. If an adequate statistical description of the size distribution of a sediment is desired, Shaker 1 is the best type to select for that purpose.

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APPENDIX

TABLE 4. *Results of various mechanical analyses of four splits of river sand*
(Figures in roman type are weight in grams; figures in italics are weight percentages.)

Split	Time in minutes	Shaker	Mechanical analysis						
			−2 to −1φ 4–2 mm	−1 to 0φ 2–1 mm	0 to 1φ 1–.5 mm	1 to 2φ .5–.25 mm	2 to 3φ .25–.125 mm	3 to 4φ .125–.062 mm	>4φ <.062 mm
A	5	1	0.31 *0.3*	2.63 *2.3*	30.95 *27.5*	57.49 *51.1*	11.36 *10.1*	4.38 *3.9*	5.40 *4.8*
B	5	1	0.40 *0.4*	2.67 *2.4*	31.46 *28.2*	56.57 *50.7*	10.86 *9.7*	4.16 *3.7*	5.36 *4.8*
B	5	1	0.37 *0.3*	2.68 *2.4*	31.53 *28.3*	56.43 *50.7*	10.78 *9.7*	4.30 *3.9*	5.15 *4.6*
B	5	1	0.37 *0.3*	2.66 *2.4*	31.31 *28.1*	56.71 *51.0*	10.86 *9.8*	4.16 *3.7*	5.22 *4.7*
B	5	1	0.35 *0.3*	2.63 *2.4*	31.38 *28.2*	56.60 *50.9*	10.88 *9.8*	4.16 *3.7*	5.21 *4.7*
C	5	1	0.47 *0.4*	2.58 *2.4*	31.02 *28.7*	54.35 *50.2*	10.81 *10.0*	3.95 *3.6*	5.04 *4.7*
D	5	1	0.17 *0.2*	2.51 *2.4*	29.53 *28.0*	53.79 *51.0*	10.46 *9.9*	3.91 *3.7*	5.03 *4.8*
A	10	1	0.32 *0.3*	2.61 *2.3*	30.74 *27.3*	57.48 *51.1*	11.43 *10.2*	4.20 *3.7*	5.63 *5.0*
B	10	1	0.40 *0.4*	2.56 *2.3*	31.05 *27.9*	56.64 *50.9*	11.08 *10.0*	4.10 *3.7*	5.45 *4.9*
C	10	1	0.42 *0.4*	2.56 *2.4*	30.42 *28.2*	55.00 *50.9*	10.73 *9.9*	3.95 *3.7*	4.92 *4.6*
D	10	1	0.17 *0.2*	2.46 *2.3*	29.12 *27.6*	54.04 *51.3*	10.60 *10.1*	3.94 *3.7*	5.07 *4.8*
A	60	1	0.32 *0.3*	2.52 *2.2*	29.38 *26.1*	57.91 *51.5*	12.32 *11.0*	4.10 *3.6*	5.84 *5.2*
B	60	1	0.35 *0.3*	2.44 *2.2*	30.21 *27.1*	56.86 *51.1*	11.81 *10.6*	3.84 *3.5*	5.79 *5.2*
C	60	1	0.39 *0.4*	2.48 *2.3*	29.57 *27.3*	55.06 *50.8*	11.56 *10.7*	3.72 *3.4*	5.53 *5.1*
D	60	1	0.16 *0.2*	2.38 *2.3*	27.88 *26.4*	54.89 *52.0*	11.07 *10.5*	3.68 *3.5*	5.42 *5.1*

TABLE 4 (*continued*)

Split	Time in minutes	Shaker	Mechanical analysis						
			−2 to −1φ 4–2 mm	−1 to 0φ 2–1 mm	0 to 1φ 1–.5 mm	1 to 2φ .5–.25 mm	2 to 3φ .25–.125 mm	3 to 4φ .125–.062 mm	>4φ <.062 mm
A	60	1	0.29	2.44	29.47	57.84	12.17	4.08	5.94
	+10	H	*0.3*	*2.2*	*26.3*	*51.5*	*10.8*	*3.6*	*5.3*
B	60	1	0.32	2.42	29.80	57.12	11.83	3.86	5.74
	+10	H	*0.3*	*2.2*	*26.8*	*51.4*	*10.6*	*3.5*	*5.2*
C	60	1	0.39	2.41	29.20	55.55	11.40	3.97	5.27
	+10	H	*0.4*	*2.2*	*27.0*	*51.3*	*10.5*	*3.7*	*4.9*
D	60	1	0.15	2.36	28.16	54.30	11.34	3.71	5.41
	+10	H	*0.1*	*2.2*	*26.7*	*51.5*	*10.8*	*3.5*	*5.1*
A	5	2	0.38	2.74	33.74	56.75	9.88	4.45	4.89
			0.3	*2.4*	*29.9*	*50.3*	*8.8*	*3.9*	*4.3*
A	5	2	0.38	2.74	33.68	56.74	9.84	4.47	5.00
			0.3	*2.4*	*29.8*	*50.3*	*8.7*	*4.0*	*4.4*
A	5	2	0.33	2.75	33.71	56.74	9.88	4.49	4.87
			0.3	*2.4*	*29.9*	*50.3*	*8.8*	*4.0*	*4.3*
A	5	2	0.33	2.76	33.84	56.46	10.00	4.47	4.86
			0.3	*2.4*	*30.0*	*50.1*	*8.9*	*4.0*	*4.3*
B	5	2	0.46	2.75	34.27	55.77	9.51	4.30	4.79
			0.4	*2.5*	*30.6*	*49.9*	*8.5*	*3.8*	*4.3*
C	5	2	0.48	2.69	33.52	54.13	9.27	4.18	4.47
			0.4	*2.5*	*30.8*	*49.8*	*8.5*	*3.8*	*4.1*
D	5	2	0.34	2.66	32.17	53.18	9.03	4.05	4.41
			0.3	*2.5*	*30.4*	*50.2*	*8.5*	*3.8*	*4.2*
A	10	2	0.35	2.74	33.35	56.99	10.00	4.43	5.13
			0.3	*2.4*	*29.5*	*50.4*	*8.9*	*3.9*	*4.5*
B	10	2	0.41	2.77	33.86	56.07	9.57	4.23	4.98
			0.4	*2.5*	*30.3*	*50.1*	*8.6*	*3.8*	*4.5*
C	10	2	0.49	2.63	33.24	54.24	9.43	4.13	4.70
			0.5	*2.4*	*30.5*	*49.8*	*8.7*	*3.8*	*4.3*
D	10	2	0.23	2.54	31.84	53.40	9.18	3.97	4.51
			0.2	*2.4*	*30.1*	*50.5*	*8.7*	*3.8*	*4.3*
A	60	2	0.28	2.56	32.39	58.09	10.06	4.50	5.24
			0.2	*2.3*	*28.6*	*51.4*	*8.9*	*4.0*	*4.6*
B	60	2	0.42	2.56	33.04	56.50	9.95	4.17	5.27
			0.4	*2.3*	*29.5*	*50.5*	*8.9*	*3.7*	*4.7*
C	60	2	0.33	2.45	32.64	54.75	9.56	4.04	4.98
			0.3	*2.3*	*30.0*	*50.3*	*8.8*	*3.7*	*4.6*
D	60	2	0.22	2.51	31.25	53.86	9.33	3.87	4.85
			0.2	*2.4*	*29.5*	*50.9*	*8.8*	*3.7*	*4.6*

(*continued on next page*)

TABLE 4 (*continued*)

Split	Time in minutes	Shaker	Mechanical analysis						
			−2 to −1φ 4–2 mm	−1 to 0φ 2–1 mm	0 to 1φ 1–.5 mm	1 to 2φ .5–.25 mm	2 to 3φ .25–.125 mm	3 to 4φ .125–.062 mm	>4φ <.062 mm
A	60	2	0.28	2.53	31.32	57.67	11.05	3.73	5.63
	+10	H	*0.2*	*2.3*	*27.9*	*51.4*	*9.8*	*3.3*	*5.0*
B	60	2	0.43	2.50	31.82	56.83	10.63	4.08	5.36
	+10	H	*0.4*	*2.2*	*28.5*	*50.9*	*9.5*	*3.7*	*4.8*
C	60	2	0.41	2.42	30.95	55.33	10.33	3.90	5.14
	+10	H	*0.4*	*2.2*	*28.5*	*51.0*	*9.5*	*3.6*	*4.7*
D	60	2	0.16	2.35	29.70	54.17	10.11	3.75	5.10
	+10	H	*0.2*	*2.2*	*28.2*	*51.4*	*9.6*	*3.6*	*4.8*
A	5	3	0.15	2.73	37.16	55.85	7.10	4.94	3.88
			0.1	*2.4*	*33.2*	*50.0*	*6.4*	*4.4*	*3.5*
B	5	3	0.41	2.76	37.36	55.05	6.75	4.76	3.68
			0.4	*2.5*	*33.7*	*49.7*	*6.1*	*4.3*	*3.3*
C	5	3	0.52	2.78	36.14	53.85	6.70	4.52	3.58
			0.5	*2.6*	*33.4*	*49.8*	*6.2*	*4.2*	*3.3*
C	5	3	0.50	2.63	36.52	53.55	6.75	4.52	3.46
			0.5	*2.4*	*33.8*	*49.6*	*6.3*	*4.2*	*3.2*
C	5	3	0.60	2.75	36.46	53.45	6.75	4.44	3.48
			0.6	*2.5*	*33.8*	*49.5*	*6.3*	*4.1*	*3.2*
C	5	3	0.52	2.65	36.54	53.47	6.75	4.46	3.47
			0.5	*2.5*	*33.9*	*49.6*	*6.3*	*4.1*	*3.2*
D	5	3	0.75	2.58	34.66	52.95	6.55	4.42	3.58
			0.7	*2.4*	*32.9*	*50.2*	*6.2*	*4.2*	*3.4*
A	10	3	0.36	2.65	36.85	56.23	7.00	4.93	3.95
			0.3	*2.4*	*32.9*	*50.2*	*6.3*	*4.4*	*3.5*
B	10	3	0.38	2.58	37.05	55.57	6.76	4.64	3.88
			0.3	*2.3*	*33.4*	*50.1*	*6.1*	*4.2*	*3.5*
C	10	3	0.52	2.57	36.44	53.66	6.75	4.49	3.68
			0.5	*2.4*	*33.7*	*49.6*	*6.2*	*4.2*	*3.4*
D	10	3	0.70	2.53	34.15	53.50	6.55	4.34	3.73
			0.7	*2.4*	*32.4*	*50.7*	*6.2*	*4.1*	*3.5*
A	60	3	0.34	2.63	36.41	56.42	7.45	4.76	4.22
			0.3	*2.3*	*32.4*	*50.3*	*6.6*	*4.2*	*3.8*
B	60	3	0.41	2.58	36.73	55.56	7.16	4.59	4.14
			0.4	*2.3*	*33.0*	*50.0*	*6.4*	*4.1*	*3.7*
C	60	3	0.49	2.53	35.09	54.75	6.96	4.46	3.88
			0.5	*2.3*	*32.4*	*50.6*	*6.4*	*4.1*	*3.6*
D	60	3	0.22	2.42	33.57	54.01	6.84	4.32	3.96
			0.2	*2.3*	*31.9*	*51.3*	*6.5*	*4.1*	*3.8*

TABLE 4 (*continued*)

Split	Time in minutes	Shaker	Mechanical analysis						
			−2 to −1φ 4–2 mm	−1 to 0φ 2–1 mm	0 to 1φ 1–.5 mm	1 to 2φ .5–.25 mm	2 to 3φ .25–.125 mm	3 to 4φ .125–.062 mm	>4φ <.062 mm
A	60	3	0.18	2.33	30.29	61.19	8.17	4.74	4.58
	+10	H	*0.2*	*2.1*	*27.2*	*54.9*	*7.3*	*4.3*	*4.1*
B	60	3	0.32	2.33	30.44	60.35	8.03	4.48	4.50
	+10	H	*0.3*	*2.1*	*27.6*	*54.6*	*7.3*	*4.1*	*4.1*
C	60	3	0.50	2.33	30.64	58.46	7.65	4.26	4.00
	+10	H	*0.5*	*2.2*	*28.4*	*54.2*	*7.1*	*4.0*	*3.7*
D	60	3	0.64	2.40	28.94	57.35	7.55	4.29	4.13
	+10	H	*0.6*	*2.3*	*27.5*	*54.5*	*7.2*	*4.1*	*3.9*
A	10	H	0.32	2.49	31.03	57.95	10.70	4.50	5.25
			0.3	*2.2*	*27.6*	*51.6*	*9.5*	*4.0*	*4.7*
B	10	H	0.37	2.44	31.44	57.21	10.23	4.32	5.08
			0.3	*2.2*	*28.3*	*51.5*	*9.2*	*3.9*	*4.6*
C	10	H	0.46	2.35	31.03	55.35	10.04	4.24	4.82
			0.4	*2.2*	*28.7*	*51.1*	*9.3*	*3.9*	*4.5*
D	10	H	0.20	2.31	29.88	54.33	9.70	4.02	4.90
			0.2	*2.2*	*28.4*	*51.6*	*9.2*	*3.8*	*4.7*

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APRIL, 1946

CARNALLITE-FILLED MUD CRACKS IN SALT CLAY[1]

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ABSTRACT

Vertical stringers of carnallite and clay in carnallitic salt clay of the Salado formation exhibit a mud-crack pattern in plan, and die out at the base of the salt clay where it overlies clean halite. They are interpreted as mud cracks filled during deposition.

The mine of the Potash Company of America is situated about 20 miles northeast of Carlsbad, New Mexico, in and around sec. 4, T. 20 S., R. 30 E., N.M. P.M. It produces potash from a single zone in the Salado formation. This zone is 4 to 8 feet thick, lies at a depth of about 900 feet, and consists of a mixture of sylvite and halite.

The principal marker in the potash-mines area is a bed of anhydrite, generally 5 to 8 feet thick and here 35 to 50 feet above the producing zone. The marker bed also contains some polyhalite and locally a few blebs of sylvite. About 30 to 40 feet below the anhydrite bed and only a few feet above the sylvite zone that is mined is a thin polyhalite bed a few inches to two feet thick, locally split by a halite parting a few inches thick. In the ordinary course of mining this thin polyhalite bed and the beds above it are seldom cut, hence data concerning them are scanty.

In an overcast at panel northeast 23 east 1 north, which is in sec. 34, T. 19 S., R. 30 E., beds lying 15 to 20 feet above the producing zone were cut. In the upper part of the walls and in the top of the cut were revealed several roughly vertical stringers of carnallite in salt clay. The cut did not extend high enough to show the upper termination of the stringers. They thin downward, and pinch out at the base of the salt clay where it grades rapidly into clean solid halite, 6 to 8 feet thick, which overlies the polyhalite. In the ceiling the stringers follow a coarse mud-crack pattern. The stringers are 3 to 5 feet apart, and their width does not exceed 2 inches. The carnallite in the stringers is mixed with some clay, and both the carnallite and the clay in the stringers are like those of the adjacent salt clay, differing only in relative abundance.

The salt clay is a mixture of clear halite and dark reddish-brown clay containing some blebs of sylvite or carnallite or both, as shown by nearby core-drill holes. In the overcast the blebs are carnallite, which is colored dark purplish brown, presumably by dispersed clay particles. One of the nearby drill holes showed a 2-inch layer of carnallite overlying the salt clay and overlain by a 2-inch layer of green clay, above which was clean solid halite.

The fissures are restricted to the clayey bed, not extending into the underlying halite, and they have the polygonal pattern of mud cracks. Carnallite was available for filling mud cracks during and immediately after deposition of the salt clay, but thereafter the sediment was halite. The carnallite stringers are therefore interpreted as fillings in mud-cracks at the time of deposition.

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

JOURNAL OF SEDIMENTARY PETROLOGY, Vol. 16, No. 1, PP. 15–18
FIG. 1, TABLE 1, APRIL, 1946

VOLCANIC SEDIMENTS IN NORTH TEXAS

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ABSTRACT

Volcanic sediments, known as pumicite, ranging in thickness from eight inches to 35 feet are present in North Texas. The materials accumulated in basins which had been almost filled with recent sediments. The pumicite was erupted during two periods of igneous activity. The first (oldest) was probably in late Pliocene; the youngest was in Pleistocene.

INTRODUCTION

Volcanic sediments commonly known as pumicite, or volcanic ash, are fine grained, glassy materials ejected by volcanoes. Individual particles include broken angular fragments and unbroken glass bubbles of various shapes. Pumicite is found in North Texas in the High Plains region and in the adjacent plains to the east (fig. 1). The deposits are widely distributed, completely isolated, and form only a small portion of the rocks of the region.

Accumulation of pumicite was restricted to basins that were probably former lakes or ponds; a few appear to have resulted from the local widening of stream valleys. Areal extent of the deposits is small, seldom, if ever, covering more than a few acres. The thickest exposure observed is 35 feet in Collingsworth County, and the thinnest is eight inches in Crosby County.

The purpose of this paper is to describe the majority of the pumicite deposits in North Texas and to investigate the possibility of their correlation and probable source by physical and chemical characteristics. Most of the known pumicite deposits (Sellards and Baker 1934) in Lynn, Scurry, Collingsworth, Swisher, Briscoe, Crosby, Hemphill, Roberts, Dickens, Kent, and Hartley counties are described. As pumicite is not easily recognized except in fresh exposures, it is expected that other deposits will be discovered in these and adjacent counties.

Outcrops of the pumicite in the above counties were visited jointly by the writers. Field work involved collecting samples for detailed analysis and making a general survey of the deposits as to thickness, horizontal extent, stratification, and relations to the enclosing beds.

To obtain a representation of the deposit as a whole for laboratory analysis, materials in collected samples representing different horizons were mixed together. Sizing of constituent ash particles was determined for each deposit by the use of Tyler standard screens. The several particle size groups were studied under the binocular and petrographic microscopes for characteristics of individual shards, foreign matter, and extent of alteration.

DISTRIBUTION OF THE PUMICITE DEPOSITS

1. Lynn County—Two deposits are exposed. One is about six miles south of the town of Tahoka and one-half mile west of highway 87. The other is on Spring Creek near the Garza-Lyn county line.
2. Scurry County—Pumicite is exposed about 10 miles east of the town of Snyder on state highway 15.
3. Kent County—The largest deposit is exposed on Duck Creek, two miles west and three miles south of the town of Girard. Pumicite crops out in cultivated fields near Girard.
4. Dickens County—Pumicite is exposed on a tributary of South Pease River, two miles north of the town of McAdoo.
5. Crosby County—About 11 miles

north of the town of Crosbyton, an eight inch layer of pumicite is exposed in the road cut adjacent to Mount Blanco.

6. Swisher County—Exposures of pumicite are confined to Tule Creek drainage basin. The largest is on the north side of Tule Canyon near the posits are concentrated in Buck Creek and Wolf Creek drainage basins.
9. Roberts County—Pumicite is exposed at the head of Indian Creek, about nine miles northwest of the town of Miami.
10. Hartley County—Pumicite is the

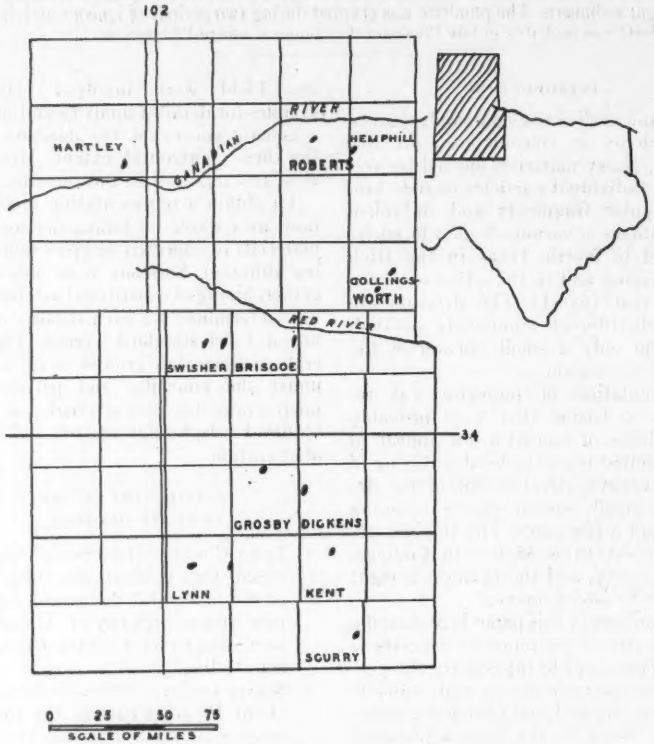

FIG. 1.—Map showing location of pumicite deposits.

Brisco-Swisher county line. A smaller deposit is in the road cut at "Rock Crossing" in central Swisher County.

7. Briscoe County—Pumicite crops out at the edge of the "Caprock" on the Silverton-Clarendon highway.
8. Collingsworth County—Pumicite de-

cap rock in a small monadnock about eight miles west of the town of Channing.

11. Hemphill County—Pumicite is exposed about one mile east of the Roberts-Hemphill county line on the former Miami-Canadian highway.

CHARACTERISTICS OF THE PUMICITE

Pumicite in North Texas was probably supplied during two periods of igneous activity. The first or oldest period, late Pliocene, is represented by the deposit in Hemphill County. Materials in this deposit are highly indurated, dull white, and attain a maximum thickness of seven feet. Devitrification has proceeded sufficiently to remove most of the glassy luster and to produce an abundance of montmorillonite and a minor quantity of iron oxide. In addition, some of the glass has been altered to opaline material which is dull white, opaque, and weakly fluorescent. Overburden consists of about five feet of sandy clays that are highly impregnated with caliche. Underlying the ash are sandy clays from which Pliocene vertebrate fossils have been collected (Reed and Longnecker, 1932).

The second period of igneous activity, early Pleistocene, supplied ash for the majority of the deposits in North Texas. Materials in these deposits have characteristics that are strikingly similar. These include: type and shape of fragments, fluting, inclusions, crystallites, color, silica content, and the presence of feldspar. Particles of pumicite are angular, commonly three to five-sided, concave-sided, and consist of single and multiple bubbles and bubble wall fragments. All fragments are transparent and under reflected light have much the appearance of powdered glass. Well developed fluting was noted parallel to the long axis of the fragments. Bubble inclusions are common; some are drop-like, others are elongated. Crystallites consisting of globulites and belonites are present on many of the shards. The ash is bluish-white but changes to dark gray upon exposure. Products of devitrification consisting of montmorillonite and dull white opaline materials are variable in different deposits but they do not completely obscure the characteristics of the individual particles. The ash in some deposits is slightly indurated and compact, in others it is loose and powdery, and a few deposits contain beds of both types. Small quantities of quartz and feldspar were noted. Index of fraction of the volcanic ash in various deposits (lowest 1.50, highest 1.515) denotes, according to George (1924), a high silica content ranging from 68 to 70 per cent. Overlying the ash deposits are wind blown sands and locally thin layers of flaggy limestone: below it are stratified sands and gray bentonitic clays which in some of the basins contain Pleistocene vertebrate fossils.

TABLE 1. *Showing percentage of ash retained on different mesh screens and the silica content as determined from index of refraction*

County	Mesh of screens				Index of Refract.	Silica content
	65	100	200	200+		
Scurry	1.9	45.2	38.8	14.1	1.51	69
Collingsworth-Buck Ck	5.3	33.5	40.0	21.2	1.51	69
Collingsworth-Wolf Ck	.5	10.5	45.5	43.5	1.51	69
Dickens	1.2	19.3	41.0	38.5	1.515	68
Lynn-Tahoka	.9	15.3	53.8	30.0	1.51	69
Lynn-Spring Ck	1.3	14.0	45.9	38.8	1.515	68
Swisher	1.3	7.6	45.9	45.2	1.515	68
Kent	4.0	19.7	50.0	26.3	1.51	69
Briscoe	.6	13.5	48.8	37.1	1.515	68
Roberts	2.9	30.0	45.3	21.8	1.515	68
Hartley	4.8	21.6	47.2	26.4	1.51	69
Hemphill	—	—	—	—	1.50	70
Crosby	—	—	—	—	1.50	70

CONCLUSIONS

Deposits of volcanic sediments in North Texas are widely distributed, completely isolated, and attain a maximum thickness of 35 feet. These sediments were probably ejected during two periods of igneous activity, late Pliocene and early Pleistocene. Pumicite of Pliocene age is exposed in Hemphill County. It is highly indurated and contains an abundance of montmorillonite and dull white opaline materials. The remaining deposits accumulated during early Pleistocene. The materials are slightly altered and have characteristics in the different occurrences that are strikingly similar.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 16, NO. 1, PP. 19–40
FIGS. 1–30, TABLE 1, APRIL, 1946

INTERPRETATION OF THE RESULTS OF MECHANICAL ANALYSES[1]

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ABSTRACT

Mechanical analyses of deposits of various sedimentary environments have been made by means of a new type of sedimentation balance for grain sizes from 500 to 5 μ. The results have been plotted on arithmetic probability paper. Well-sorted sands give on this paper straight lines proving that they have a symmetrical size frequency distribution when an arithmetic grade scale is used. The size frequency distribution of the sand and silt grades of argillaceous sediments commonly is a part of a symmetrical one.

The arithmetic probability paper enables us to study the phenomena caused by the differentiation of the transported detritus. Three main types of frequency distribution called R-, S- and T-types occur in sedimentary deposits due to the sorting of the transporting medium. The characteristic features of a sedimentary size frequency distribution are found in the extremes and not in the central half of the distribution. Statistical values based on quartiles, therefore, do not give satisfactory results.

The characteristic shape of the extremes of the distributions caused by the differentiating action are frequently blurred by later mixing of material due to variations in the capacity of the transporting medium. Composite frequency distributions, however, are commonly recognized if the results are plotted on the probability paper.

As far as analyses by means of the sedimentation balance have been made sedimentary environments can be recognized by the predominance or alternation of certain frequency distributions.

INTRODUCTION

During the years 1940–1945, in which Holland has been occupied and terrorized by the Germans, the continuous inflow of samples of sedimentary rocks for mineralogical analysis from the oilfields of the Royal Dutch-Shell Group stopped and the writer was allowed to introduce a research program, which was carried out in the sedimentary petrological laboratory of the N. V. De Bataafsche Petroleum Maatschappij in Amsterdam.

One of the items of this program has been devoted to the mechanical analysis and the results of these investigations, which have been published in the Dutch language (with English Summary) (Doeglas 1941, 1944 and 1945 a-e), will be summarized here in order to make them more common knowledge.

Mechanical analyses have been used a long time and almost too many papers deal with the interpretation of their results. If, however, we use these for the interpretation of the geological history of sedimentary rocks or for the determination of the facies of formations we soon notice that they do not give many more data than the megascopical description.

In a general way the average size can be correlated with the strength of the transporting medium. The results of more than 1000 analyses of deposits of different origin (Wentworth, 1919), however, indicate that in a definite sedimentary environment the size frequency distribution varies considerbaly.

Since 1920 many authors, e.g. Wentworth, Trask, Niggli and Krumbein, have tried to fix the size frequency distribution by various statistical coefficients. Although Krumbein and Aberdeen (1937) found that these values have a geographical distribution in a certain area, they do not give geologists information about the origin of the deposits and of the circumstances which prevailed during the deposition. During fieldwork the geologist has an opportunity to study the variations of the composition of

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sedimentary layers horizontally and stratigraphically. When the time devouring mechanical analysis does not provide new data, it can only be used for special objects, e.g. for technical and agricultural purposes and for classification.

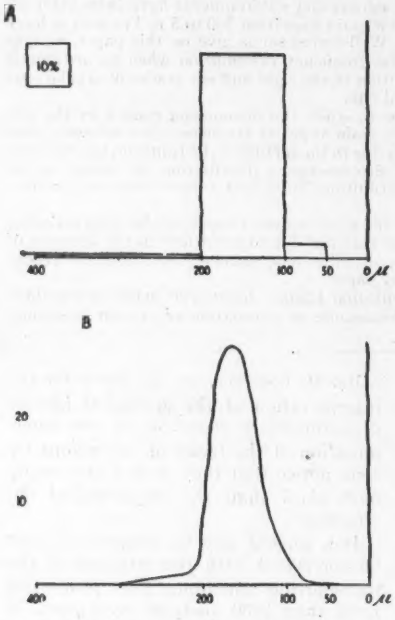

FIG. 1.—Influence of the number of grades on the accuracy of the distribution.
A Histogram, fixed by 3 grades.
B Frequency curve. Fixed by many grades (10 μ intervals).

In his first paper the author summarized the aim of the mechanical analysis as follows:

1. A more exact representation of the megascopical description.
2. Determination of the environment. This includes the distinction between aeolian, fluviatile, lacustrine, marine and other deposits and also the knowledge of the physical properties of the transporting medium, e.g. capacity, current-velocity and wave action.
3. Study of the progressive change of the size in the direction of transport.
4. Correlation of the size frequency distribution with the porosity and permeability.
5. Correlation between the type of current and the transported and deposited detritus, if possible in cooperation with hydrologists.

Mechanical analyses should be made with these objects in mind. The items 2 and 5 are the most important for geological studies. The author studied the hydrological (potamological) literature in the hope that a relation between the size frequency distribution and the capacity or velocity of a current might be found. This hope proved to be idle. Potamologists generally use an average size for correlation. Mechanical analyses of the suspended material are seldom made.

Hjulström and others, however, mention the sensitiveness of fine sand and silt grades for small variations in capacity. This means that these grades should be closely analyzed. Such accurate data are not available and we must start with the analysis of recent deposits and of detritus during transport.

The mechanical analysis of the sand and silt grades ought to be made accurately. The question arose as to whether the commonly used grades fulfilled these requirements. The Wentworth- and Atterberg-intervals resemble each other in the sand-silt-grades. Figure 1 shows the difference between a sieve (A) and a more detailed analysis (B) of an Eocene sand from the Paris Basin. Figure 2 represents the influence of the choice of the grade limits on the shape of the histogram for a symmetrical frequency distribution. As we like to study small variations in the size of the sand and silt grades, we need a more accurate analysis than can be made with the normal sets of sieves.

METHOD OF MECHANICAL ANALYSIS

Van Veen (1936) used for a rapid and

reliable determination of the grain size of bottom samples of the North Sea a large sedimentation cylinder. This cylinder is 200 cm. long and has a diameter of 10 cm. The lower part is conical and ends in a glass tube. The volume of the settled particles is measured. This apparatus was introduced in our laboratory in 1939. The determination of the volume of the settled particles, however, proved to be not very satisfactory and the apparatus has been rebuilt for measurement of the weight percentage. This apparatus is shown schematically in figure 3. The lower part of the cylinder can be removed. The sedimentary particles settle at a depth of 200 cm. upon a disk, suspended with a stainless steel wire from the arm of a balance placed above the cylinder. This balance has been constructed in such manner that when 4 grams of quartz are placed under water on the disk, the free arm moves a definite distance along a graduated scale. This scale is divided into 100 parts and the percentage of the material settled on the disk can be read off at any time interval. If more or less than 4 grams of quartz is taken the percentage can be converted to 4 grams=100 per cent.

Sedimentary material does not consist of quartz only. Also heavy minerals (specific gravity >2.895) occur in small amounts. In other sands platy minerals (mica) may be abundant. These minerals have settling velocities differing from that of quartz. The settling velocity of spherical grains of quartz differs from that of irregularly shaped ones. During deposition in natural environments these differences are present too, except for aeolian deposits.

Between 500 and 5 μ, the error made by analyzing duplicate samples is less than 2 per cent. Above 500 μ the error gets larger due to deviations by the deposition of the material on the cylinder and the short settling-time. The grains <5 μ form a suspension which owing to its slightly higher specific gravity flows over the edges of the disk. These fine grades are removed beforehand by decantation. For a complete analysis these fine grades are being analyzed by the pipette method. The grades >500 μ are sieved in the usual manner. Argillaceous sediments are treated according to the scheme given by the Agricultural Education Association (1926).

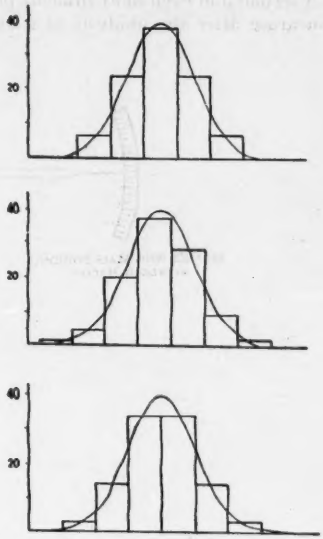

FIG. 2.—Influence of the choice of grade-limits on the shape of the histogram (after Gry, 1938).

The settling-times have been calculated according to the formula of Sudry (1912), which agreed excellently with our experimental data. One error is made due to the use of 4 grams of material. This quantity of sand cannot be brought into the cylinder without causing some turbulence of the upper 20 cm. The settling velocity in the upper part of the column therefore is too large. In a following paper I will describe the deviations caused by the use of 4 grams of material and give tables for the determination of the size.

The determination of the size of sediments in small intervals has given important clues for the interpretation of the size frequency distribution.

GRAPHIC PRESENTATION

A second and even more difficult problem arose after the analysis of a small number of sediments. The size frequency distribution of these deposits had been fixed by many data which we had to digest. How to present these data? The mathematical values calculated according to the formulae of Trask, Niggli or Krumbein would be more accurate than those for sieve-analyses. Would they,

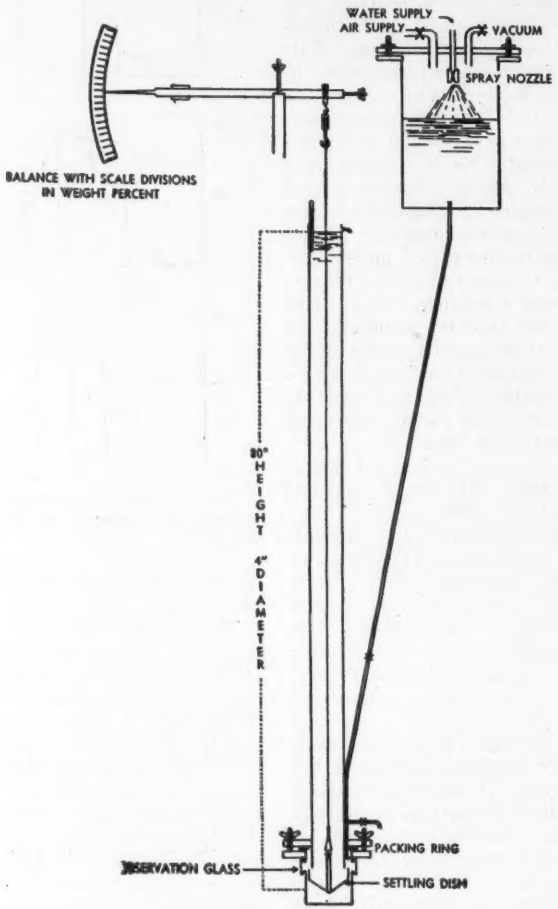

FIG. 3.—Sedimentation balance for quartz of 500–5 μ.

however, give more useful data for the interpretation of the results? The values based on the quartiles only refer to the middle part of the frequency distribution. Is this part of the distribution the most important or would the material coarser than the third and smaller than the first quartile give us useful facts? Other values give the deviations with respect to a definite symmetrical distribution, e.g. the probability distribution. Are these symmetrical curves, however, the fundamental type of the size frequency distribution of sediments? Should we use a logarithmic or an arithmetic grade scale?

Not being able to solve all these mathematical and statistical problems I called in the aid of Brezesinska Smithuysen. The first question he asked me, was: "Is there any function between the size and the weight percentage?" The only answer I could give was: "I don't know." The second question was: "What would you like to know?" and I showed him the five points of the problem. He studied the literature and his conclusion was: Try out several statistical methods till you find the one that suits your problem. He advised me to work graphically and proposed the use of a probability paper with an arithmetic size-scale for the following reasons:

1. Many sediments have a more or less symmetrical size frequency distribution. This could easily be checked on probability paper. Deviations from a symmetrical curve could be studied. Cumulative percentages were obtained by the investigation with the sedimentation-balance, a cumulative curve therefore should be used.
2. The size of the grains was determined by the settling velocity and the abcisis should give the settling time. In my opinion this was not very convenient and Smithuysen decided to use the square root of the reciprocal value of the settling time which is proportional to the diameter of the grains.[2] The presentation of the data thus fitted in with the method of analysis.

I must state here that we do not suppose that the fundamental size frequency distribution of sediments is a probability distribution. The probability paper only gave us a simple graphic method to start with.

RESULTS OF THE FIRST DETAILED ANALYSES

Plotting our data on this paper (fig. 5) we obtained between 10 and 90 per cent several more or less straight lines indicating that many sediments have a nearly symmetrical size frequency distribution when the grade scale is arithmetic. Using a logarithmic scale nearly all curves are bent to the right when the curve is followed from coarse to fine (fig. 4). The curves are then apparently straight only in the fine clay fractions. This, however, is generally due to the horizontal trend of the curves. Care

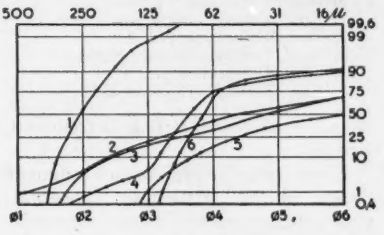

FIG. 4.—Cumulative curves of sediments plotted on logarithmic probability paper (phi-limits according to Krumbein).
1. Eocene sand, near Reims, France.
2. Young marine clay near Amsterdam, Holland.
3. Tuff, North Sumatra, Netherlands East Indies.
4. Sandy clay, Eocene, near Reims, France.
5. Clay, S. E. Borneo, Netherlands East Indies.
6. Silt, Trinidad, B.W.I.

[2] According to the formula of Stokes and only for sizes $<70\ \mu$. Provisionally we use it for the entire range $400–5\ \mu$.

should be taken in use of graphs that both scales are properly equated. Vertical and horizontal scales must be in such proportion that the curves do not become too steep or too flat. This is frequently omitted.

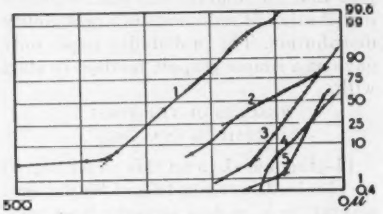

FIG. 5.—Cumulative curves of sediments on arithmetic probability paper.
1. Sand, Eocene, near Reims, France.
2. Tuff, N. Sumatra, N.E.I.
3. Sand, Tertiary, Ochiuri, Rumania.
4. Clay, S.E. Borneo, N.E.I.
5. Clay, Tertiary, Trinidad, B.W.I.

Many curves of argillaceous sediments drawn on the arithmetic probability paper are composed of two or more practically straight lines connected by rather sharp bends as presented in figures 5 and 6. This means that parts of their distribution are pieces of a symmetrical one. The question arose whether these composite curves were caused by the mixing of materials of different origins, which had themselves a symmetrical distribution. I calculated the distribution of mixtures of two and more components each having a symmetrical frequency distribution. The results of some of these calculations have been presented in the figures 7 and 8. The shape of the resultant curves of these mixtures is frequently found for sedimentary deposits. Mixtures of three and more components generally cannot be distinguished any more. If the sizes of both components overlap each other the distinction becomes more difficult. For simple cases, however, the size frequency distribution of both components can be determined. The more or less horizontal part of the curve gives the limit between both components (fig. 8). The percentage at which this

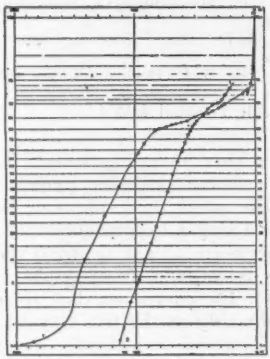

FIG. 6.—Curve 1. Sand of Fontainebleau, Montigny, France. Curve 2. Silt, Eocene, Trinidad, B.W.I.

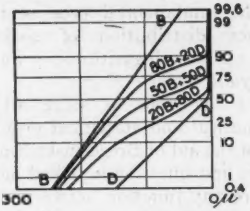

FIG. 7.—Synthetic mixture of two components (B and D), each having a symmetrical frequency distribution in the sand and silt grades. Resulting curves have been calculated.

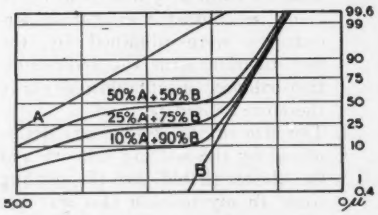

FIG. 8.—Mixtures of two components A and B having each symmetrical frequency distributions. Resulting curves have been calculated.

horizontal part occurs gives the content of the components. The frequency distribution of each component can now be calculated.

The composite frequency distribution is generally caused by the sampling of more than one homogeneous layer. Many sediments which seem to be homogeneous, however, also have composite size frequency distributions. This complex structure is caused by variations in the capacity of the transporting medium.

During transport and deposition the material is differentiated (sorted). A decline in the current velocity (capacity) causes deposition of the coarsest particles. The finer grades are carried away by rolling, saltation and in suspension. A gradual diminution of the velocity downstream causes deposits of decreasing size along the course of the stream. The maximum size of the transported material diminishes too as the coarsest grains continually settle. At a certain place the coarse grains of the originally transported detritus already have been deposited upstream, the coarsest particles present on the spot settle and the finer material is being carried downstream. The deposit itself is a fraction of the transported detritus. In order to define the shape of curves of well-sorted sediments I separated material with a symmetrical frequency distribution into several parts and calculated the frequency distribution of these parts. The curves of such fractionated distributions are given in figure 9. Curve A belongs to the original material. Curve X, which represents the distribution of the grains $>145\ \mu$, runs practically parallel to curve A in the coarse grades; below $200\ \mu$, however, it bends to the left. Curve Z (fraction $<300\ \mu$) is curved to the right between 300 and $200\ \mu$, afterwards runs parallel to curve A. Curve Z represents the fraction $300–145\ \mu$ from the original material A; it has a sinuous form. At the coarse end it is bent to the right and at the fine end to the left.

All these theoretical assumptions were laid down in a first paper written together with Brezesinska Smithuysen (1941). The results of mechanical analyses of other authors could not be used as the grade limits were too widely spaced. During the following years recent deposits of dune, beach and river sands, argillaceous sands and clays from tidal mudflats and fluviatile silts and clays have been analyzed.

It was a surprise to find the shapes of the calculated curves in several detrital deposits. The sorting action of water and wind separates the transported detritus so accurately at certain sizes, depending on the capacity of the current, that frequency distributions like those of figure

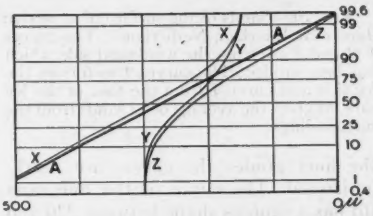

FIG. 9.—Curves obtained by removing one or both ends of a symmetrical distribution A.
Curve X: all particles $<140\ \mu$ removed.
Curve Y: all particles >300 and $<140\mu$ removed.
Curve Z: all particles $>300\ \mu$ removed.
(After Doeglas and Smithuyzen, 1941.)

9 actually occur. Later mixing may blur the characteristics, accurate sampling generally brings them out clearly.

The sinuous type Z (figure 9) was first found in dune sands. Samples had been taken of thin layers (10 mm. thick) in a profile over an active dune north of Haarlem. The north flank of this dune had been eroded by the continuous northern wind during the early spring of 1941. On the steep lee side sand had been deposited forming a fan which partly covered the vegetation. This flank had the maximum dip for loose sand. Figure 10 gives the curves of these samples and of the average composition (M) of 13 sands

from the surroundings. The samples 1 and 2 taken from the eroded part of the north flank are coarser than the average (M), the sands 5 and 6 from the steep south flank are finer. The sand at the foot of the south flank (7) again is coarser. All curves have a sharp bend to the right between 130 and 110 μ and in

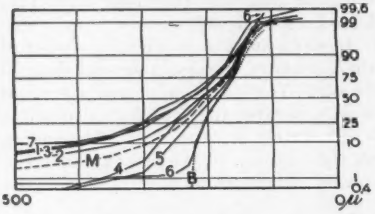

FIG. 10.—Sands of the surface of an active dune near Haarlem, Netherlands. The curves 1, 2 and 3 are from the windward side which has been eroded. The curves 4 to 6 from the lee side and curve 7 from the foot of the lee side. M gives the average of 13 sands from the surroundings.

the finer grades the curves are nearly horizontal. The curve of the fine sand (6) has a sinuous shape between 220 and 130 μ. The content of grains >220 and <130 μ is small. The dotted curve BB gives the calculative distribution of the particles <230 μ of the average dune sand (M). Curve BB practically coincides with 6, which proves that the frequency distribution of the grades 230–120 μ practically did not change. Particles >230 μ, however, have been eliminated almost entirely. Curve 6 at the fine end is slightly steeper indicating that particles <130 μ have been removed. On the south flank the entire fraction 230–130 μ of the average dune sand has been deposited, particles >230 μ lagged behind and a part of the fraction <130 μ has been carried away. The grains >230 μ remained partly in the surface layer of the north flank. Some coarse grains, however, probably rolled over the top and accumulated at the foot of the south flank, the dip being too large for these grains to settle on the steep lee side.

The sands 4 and 5 have a larger content of particles between 300 and 230 μ. In this interval the curves, however, are still bent to the right. Below 250 and 230 μ respectively, the distribution is practically the same as that of the average dune sand.

Sands having sinuous curves are not only found on the lee side of dunes, they occur in places where the current diminishes due to vegetation or topographical features. In water the same phenomenon is found. The velocity of the current, however, must be rather constant and sands having this type of distribution generally are only found in thin layers. Small variation in the velocity causes a straightening of the curves due to the deposition of slightly coarser and fine material. When now and then large fluctuations in the velocity occur, still coarser and/or finer grains may be deposited and the curves become more and more asymmetrical. One or both extremes of the curve get an extension (a "tail") as the curves of figure 10. In the dune sands of Holland the finest particles are even <1 μ, although 95–99 per cent is coarser than 110 μ. These fine

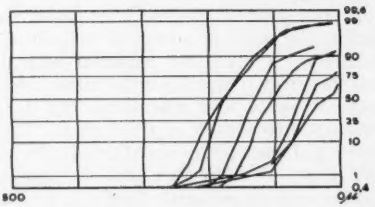

FIG. 11.—Tidal flat deposits.

particles have been deposited when the wind ceases. In overgrown areas the content of this fine material increases, in deflated parts its percentage is low.

The fine sands of tidal mudflats have similar curves. The tail at the coarse end is commonly small, many curves are bent to the right at this end. These deposits (fig. 11) are decidedly sandy or silty, but contain, however, varying per-

centages of fine particles. The curves are steep and fairly straight in the coarsest 90 per cent, then curve to the right. The fine part is practically horizontal up to 2μ and afterwards bends sharply to 100 per cent. The content of the fine grains generally varies from 1 to 10 per cent. It may, however, increase to 60 per cent, as shown in figure 11. The deposition of the fine grades must be due to the turn of the tide, during which the velocity drops to zero, or to the supply of larger particles of clay eroded elsewhere in the area. The presence of grains of older clay formations in the water has been proved for the Dutch

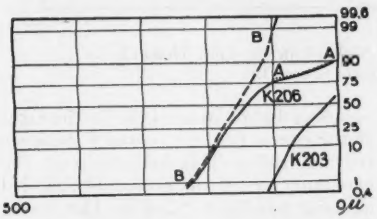

FIG. 12.—Tidal flat deposits. The curves 203 and 206 are from two samples 20 cm. apart. Curve AA has the same distribution as 203 and is equal to the tail of 206. Curve BB represents the distribution of the material of 206 > 100 μ.

tidal mudflats. The author was able to show that clay deposits having size frequency distributions identical with those of the tail of the sands, occurred in the same area. The curves 203 and 206 (fig. 12) are from samples of two layers about 20 cm. apart. The calculated size frequency distribution of the curve AA is equal to that of 203. Curve AA is identical with the tail of 206. Curve BB gives the curve of the sandy part of 206, from which the calculated tail has been removed. Mudflat sands have composite frequency distributions.

In the channels of rivers there is a continuous current. The velocity minimum never reaches zero. The fluctuations, however, are large. A certain velocity commonly dominates. Similar variations are found in the channel deposits. Commonly one size predominates. The minimum size is sharply limited and the maximum varies considerably. In the main channel the large fluctuations of the capacity bring into being a tail at the coarse end of the curve. The amount of tail material may increase considerably and the curves become slightly bent over their entire length as presented in figures 13–15. These curves are from channel deposits of the Lower Rhine and Lek in Holland between Arnhem and Rotterdam. The content of the tail material decreases downstream. The minimum size varies slightly as is shown in the figures 13–15. These figures present the deposits in three intervals of the river. The decrease of the minimum size between the three groups, however, is distinct. The channel deposits of the Mississippi river, the Wolga, East Indian rivers and of Dutch quaternary fluviatile deposits have similarly shaped curves.

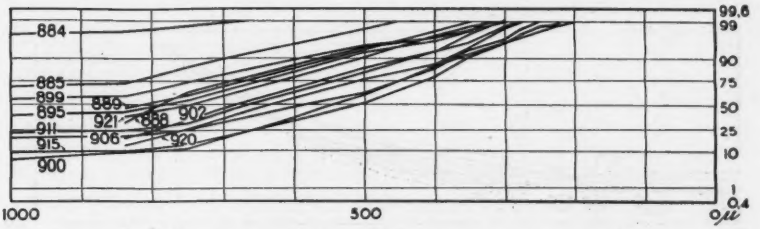

FIG. 13.—Bottom samples of the Neder-Rijn, Holland, Number of samples gives distance from source in kilometres.

The composite frequency distribution of river channel deposits is partly due to the manner of collecting the samples. These commonly are taken by means of a small type of Monaco sampler or bailing apparatus by which several layers are collected together. It is clear that the explained in two ways: 1. the fine material in the recent samples is washed out during the collection; 2. after deposition fine particles have been penetrated in the pores.

Another example of differentiation was found in fluviatile silts and clays. The

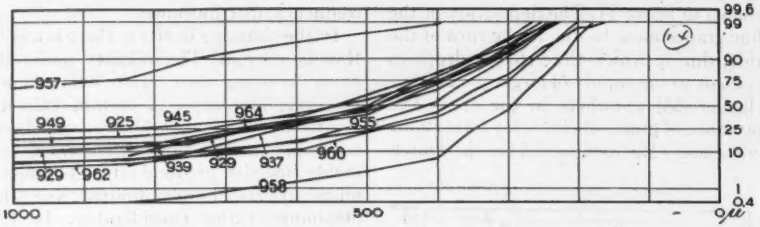

FIG. 14.—Bottom samples of the Neder-Rijn and Leik, Holland, downstream of those of figure 13.

average of such samples is complex. The author, studying Pleistocene river deposits in southeast Holland, found in gravel deposits with oblique lamination several differentiated types. Even thin clay layers occurred here and there. Mixing these types we obtain distributions equal to those of the figures 13–15. Apparently homogeneous coarse layers, however, showed complex frequency distributions. In layers, close together, I found various stages of differentiation similar to those of the dune sands south of Haarlem (fig. 10). As contrasted with the recent channel deposits, the fossil always contained very fine particles like the dune sands. All curves had a tail at the fine end. This phenomenon can be curves of figure 16 are bent to the right at the coarse end, e.g. curve F between 160 and 100 μ. This indicates that the maximum size of the originally supplied material has been >160 μ. The coarse grades must have been deposited upstream and the remaining suspension settled in its entirety. The accumulative curves of such remaining suspensions would be bent to the right at the coarse end as explained in figure 9, curve Z. Small fluctuations again straighten the curves due to the deposition of several thin layers having about the same frequency distribution. This is shown in figure 17. Curve XX is the resultant of the mixing of the components $T_A - T_E$ in the following proportion: 10% $T_A +$

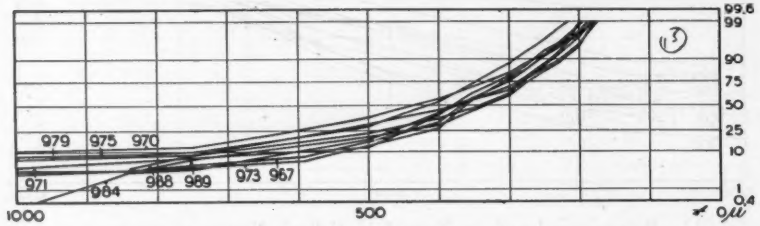

FIG. 15.—Bottom samples of the Lek, Holland, downstream of those of figure 14.

$10\% T_B + 10\% T_C + 20\% T_D + 50\% T_E$. Addition of particles $>200\ \mu$ does not make the resultant curve straight, the bend to the right remains except when the percentage of the coarse material is very large. The curves get the shape of those of figure 16. Adding grains $>200\ \mu$ to the composite deposit X of figure 17

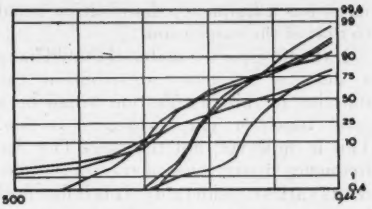

FIG. 16.—Fluviatile clays along Dutch rivers.

does not affect the shape except at the coarse end, the finer part remains straight (fig. 18). This type of curve represents clays of the marine tidal flats, of natural levees and of the deep-sea as shown in figures 19 and 20.

The above examples show that the

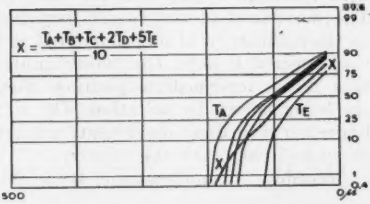

FIG. 17.—The origin of the partially straight curves of many argillaceous sediments. The curves $T_A - T_E$ represent remaining suspensions. The coarsest particles settled. Mixing of these components straightens the curve (XX).

determination of many small grade intervals gives us a clear picture of the origin of the size frequency distribution of sediments. The central half of the distribution is of little importance. The important variations lie out toward the extremes. As the values based on quartiles (Krumbein) and mean sizes (Niggli) only concern the middle part they cannot give

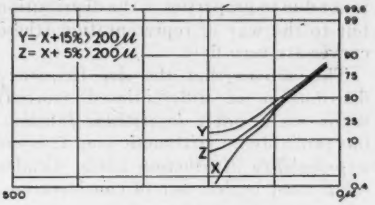

FIG. 18.—Addition of grains 200 μ does not change the main trend of the curve XX below 200 μ. It remains more or less straight.

us an insight into the origin of sedimentary deposits.

The advantage of a suitable graphic representation becomes evident too. The changes in the composition of the coarse and fine ends of the distribution are

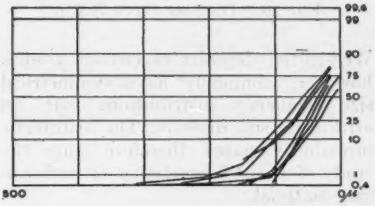

FIG. 19.—Deposits from natural levees along rivers and fine sandy clays from tidal flats.

exaggerated on the arithmetic probability paper. Many deposits have symmetrical distributions if an arithmetic grade scale is used. Even the distribution of the sandy and silty particles of many clays is commonly part of a symmetrical one.

The above characteristics stand out on millimeter paper, however, less clearly, as at the coarse and fine ends the curves are nearly always horizontal. This gives all curves a sinuous shape. On semi-logarithmic and logarithmic probability papers the phenomena may show up at

the coarse end, but naturally never at the fine. On logarithmic papers nearly all curves are bent to the right. Curves of clays are apparently straight, but this is not due to properties of the distribution but to the way of representation (these curves are very flat).

This proves that the size frequency distribution of differentiated (sorted) sediments is not a *logarithmic function*, but probably an arithmetic one. *It is not a probability distribution either.* Grades $<5\ \mu$ must be left out of consideration.

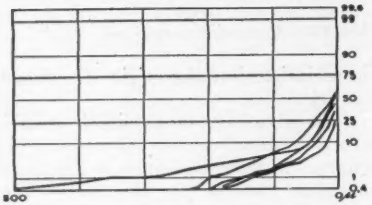

FIG. 20.—Deep-sea clays, N.E.I.

Well-sorted deposits of coarser grades, however, commonly have symmetrical size frequency distributions with an arithmetic size division. The arithmetic probability paper therefore suits the study of the differentiation of sedimentary material.

THE DIFFERENTIATION OF THE TRANSPORTED DETRITUS

Size frequency distributions of sediments give us the results of the sorting action of the transporting media. In order to study the differentiation itself we must know the composition of the originally transported material. If the source area does not contain particles $<120\ \mu$ the current cannot supply finer grains and the deposits are $>120\ \mu$. If all transported material is deposited when the current suddenly ceases, the sediment has a frequency distribution equal to that of the suspension.

If the transported material should have a definite frequency distribution the function of this distribution would be a good base for graphic representation. This is, however, not the case. The size frequency distribution of transported detritus varies considerably. It is influenced by many factors, e.g. the amount of rainfall and the presence and the amount of loose particles of different size along the courses of the main river and its tributaries.

The manner in which particles are being transported also influences the frequency distribution of the suspension. Coarse particles generally are rolling along the stream bed. The fine clay minerals are suspended and move practically with the same velocity as the current. The movement of the coarse particles, on the contrary, is often interrupted and the transport is slow. The middle grades take up an intermediate position; they are being moved by saltation. The size limits between these movements are not sharp and vary with the velocity.

According to information from the

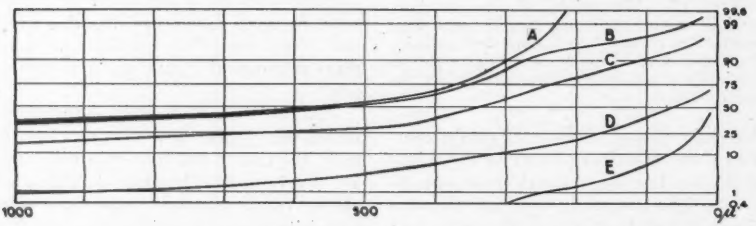

FIG. 21.—The composition of the suspended detritus in rivers. Mixing of bottom material A and fine actually suspended materials E in various proportions.

Directie van de Boven Rivieren van den Rijkswaterstaat[3] a cloud of muddy water passes the Rhine between Basel and Arnhem in two weeks.

The content of fine grades thus depends not only on the current conditions at the place of observation, but much more on those up-stream. The content of pebbles and gravel is due to local conditions. The transported material therefore consists of three main components: 1. bottom deposits of local origin; 2. fine grades from far upstream and 3. middle sizes of material less far upstream. We have seen that the bottom deposits of

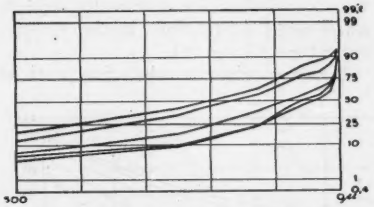

FIG. 22.—Transported material of the Missouri river near Kansas City (After Straub, 1936).

rivers had a characteristic frequency distribution (figs. 13–15). The transported material should be made up of this kind of detritus and fine sandy mud. The size frequency distribution must have about the shape of the synthetic mixtures presented in figure 21 (curves B, C and D) which have been calculated by joining varying quantities of A and E which represent the bottom material and the actually suspended particles.

To my knowledge only few mechanical analyses of transported material in rivers have been published. These data (Straub, 1936, Mohr, 1911, and Baturin, 1939) indeed are similar to the synthetic curves. Figure 22 shows the curves of suspensions of the Missouri at different heights above the bottom, figure 23 those of rivers in the East Indies. The upper curve

[3] Government Department of Public Works (Upper rivers).

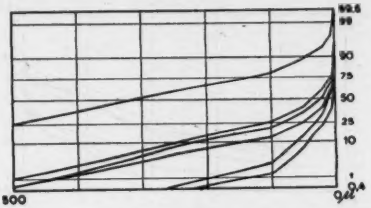

FIG. 23.—Suspended material in Neth. E. Indian rivers (After Mohr, 1911).

of figure 24 is of a suspension during flood, the lower curves of material taken at low velocities. The curves of Wolga suspensions have the same shape, rather flat above 100 μ and a stronger curvature to the left below this size. Close above the bottom the curves sometimes have a slightly more horizontal part in the silt grade, e.g. in the upper curves of figure 23 and in B and C of figure 21. This is caused by the predominance of bottom material. The slight curvature to the right in these curves occurs at the minimum size of the bottom deposits (215 μ for curve A in fig. 21). In curve D this secondary curvature is absent due to the large quantity of E.

This type of curves is found again in fluviatile clays and till (figs. 24 and 25). The current ceased and the entire suspension settled.

Notwithstanding the few observations we can be rather certain that these curves represent the average of suspensions of rivers. They are the basis for our study of the differentiation.

The differentiation of a river suspen-

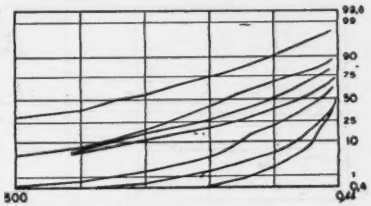

FIG. 24.—Undifferentiated fluviatile clays. Dutch rivers.

FIG. 25.—Boulder clay, Holland (After De Vries, 1942).

sion is presented schematically in figure 26, C being the average suspension. Supposing that the sorting action separates the material accurately in fractions with well limited sizes we can imitate this by cutting the frequency distribution at different sizes. The distribution of the fractions thus formed can be calculated to 100 per cent. When all particles $>780\,\mu$ settle the remaining suspension is presented by curve T_1. Similarly, the curves T_2, T_3, T_4 and T_5 give the distributions of the suspensions if the grains larger than 340, 200, 120 and 50 μ, respectively, have been deposited. R_2 gives the distribution of all fractions $>340\,\mu$ of the original suspension and S is the distribution of the fraction 340–200 μ, which is formed by deposition of the material $>200\,\mu$ from suspension T_2. The curves of the remaining suspensions always have a curvature to the right at the coarse end, the finer part is practically parallel to the curve of the suspension if this is differentiated at larger sizes (curve T_1), more or less straight if it is cut at finer sizes (T_4 and T_5). We met these curves already in river deposits (fig. 15) and in marine clays (figs. 19 and 20). As explained on page 29 these curves become practically straight when small fluctuations in the velocity occur (figs. 17 and 18).

R-curves originate when fine particles are washed out of a bottom deposit. An increase in velocity results not only in a supply and deposition of coarser detritus but simultaneously in a remodeling of earlier deposits. During this process the

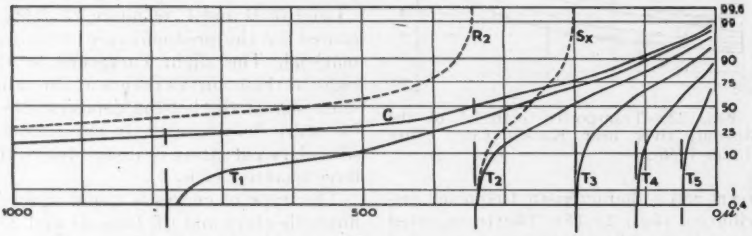

FIG. 26.—The differentiation of the transported material.

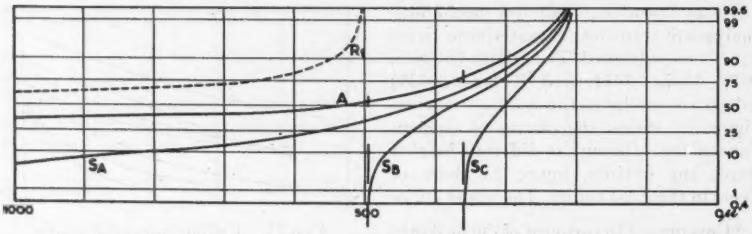

FIG. 27.—The differentiation of the bottom material in rivers (After Doeglas 1945 V).

TABLE 1

Type Differentiation	Origin	Occurrence
		Homogeneous deposits or thin layers.
R	Continuous current. Stream bed of rivers, strong marine currents, and surf action, eluvial material, erosion.	Pebbles, gravel and coarse sands, reworked older deposits (eluvium) or deposits due to sudden decrease in capacity (velocity).
S	Down-stream decreasing capacity; rood sorting action.	Lee side of dunes, banks, shallows and ripples, protected places.
T	Stagnant water, deposition of entire suspension.	Lakes, bays, inland seas, quiet places on tidal flats, natural levees and deep-sea.
Mixing		Stratified deposits and heterogeneous deposits.
R+S	Running water with varying velocities.	Stream bed of rivers, strong marine currents and wave action near beaches, shallows and cliffs.
S+T	Running water, velocity varies from zero to moderate.	Coastal deposits, sands on tidal flats, inland seas, estuaries.
do. with small amount of T		Nearly all sands have a small percentage of T-material.
R+S+T	Running water with strongly fluctuating velocities. Current now and then ceases.	(River suspensions), fluviatile clays, till, eluvial material, debris on fans and tali, mudflows.
R+S+T with large contents of T	Running water with varying velocities, of which one predominates.	In many sands.

finest grains may be removed from the surface layers. This differentiation is shown in figure 27. Curve A presents the average frequency distribution of bottom samples of rivers. By decanting all grains <500, R_1 is the distribution of the coarse residue, S_B that of the removed particles. The minimum size of the removed part is equal to that of the bottom sediment. Figure 28 gives an example of such differentiation in deposits from the Lek. B and C represent the average distribution (compare fig. 14), A is a washed out residual material and D the removed sand fraction. The separation is less accurate than in the synthetic samples of figure 28. Between 750 and 400 μ A and D contain some finer and coarser material respectively.

THE R-, S- AND T-DISTRIBUTIONS

The differentiation of the transported material causes three main types of size frequency distributions, which I called the R-, S- and T-distributions (fig. 27 and 28). These types of distribution are independent of the size. Table 1 gives a summary of their origin and occurrence.

The R-type occurs mainly in spots where the velocity is high and the bottom is eroded. Sandy and coarser bottom material of the stream-bed of rivers which is continuously remodeled, commonly has this type of curve especially in the thread of the current. Toward the banks the velocity decreases and the detritus carried on in the thread of the current is moved to the banks by turbulent cur-

rents. Here the coarsest particles settle due to the decrease of the capacity. These deposits have S-distributions with varying proportion of R. Downstream we find the same phenomenon. The capacity decreases and the coarse components are deposited. The distribution of the remaining suspension changes from T_0 to T_3. The deposits should have S-distributions if the current remained constant. The velocity in rivers, however, varies periodically and the resultant deposit is

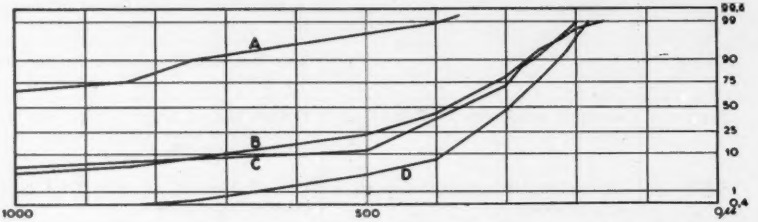

FIG. 28.—Differentiation of the average bottom deposits in the river Lek, Netherlands.

a mixture of several S-fractions. If a certain velocity predominates, the S-fraction belonging to this velocity will predominate too. Due to the decrease in capacity the maximum size of the suspension diminishes and finer S-grades are being deposited and mixed with the bottom material causing a decrease of the minimum size of the deposits. The figures 13–15 illustrate these phenomena. The fine grades are removed again due to increase of the capacity during flood.

In marine environment and in air the current is not bound to a definite channel. The variations in velocity in sections perpendicular to the stream direction are much less than in rivers and the variations in the frequency distribution of the deposits are correspondingly less. The variations are mainly due to topographical features or to vegetation. In channels and gullies between islands and on tidal mudflats we find phenomena similar to those in the stream-bed of rivers.

One must not think that the results of differentiation processes always can be recalculated to parts of the average sedimentary material in the environment. Nature seldom separates the detritus so accurately as is shown in the figures 9, 26, and 27. Subsequent mixing blurs out the characteristic shapes.

The results of the above study can be summarized as follows. There are three main types of sedimentary size frequency distributions. These are independent of the mean and the quartiles. They cannot be characterized by fixed sizes or weight percentages.

In order to define these curves we must give for each a number of sizes and the percentages which belong to them. For complex curves five values and their percentages commonly meet these requirements. We can represent these data in the following manner. Curve 1 of figure 30 is characterized by the following values: the maximum and minimum sizes and those at which the curve has a sharp bend viz. at 211, 102 and 4 μ. The maximum and minimum sizes are difficult to fix and instead of d_{max} the first percentile is used, for d_{min} the 99th percentile. The minimum size of deposits containing clay is taken at 0 μ. These data can be presented in the following formula:

$$\text{Curve 1} = \frac{494 - 211 - 102 - 04 - 00\mu}{1 - 5 - 72 - 16 - 06\%}$$

In order to fix the curvatures of the lines between these points we can add letters to the percentage of the various parts indicating the curvature, e.g. d

(dexter) for right-handed, s (sinister) for left-handed and v (varying) for undulating curves. Simpler curves need less data and the other curves of figure 30 are given as follows:

$$\text{Curve 2} = \frac{640 - 180 - 109\mu}{1 - 38 - 60\%}$$

$$\text{Curve 3} = \frac{267 - 76 - 02 - 00\mu}{1 - 4 - 77 - 18\%}$$

$$\text{Curve 4} = \frac{100 - 37 - 02 - 00\mu}{1 - 1s - 34s - 64\%}.$$

By these data the entire distribution is fixed. Composite distributions never can be fixed by statistical values.

THE DETERMINATION OF THE FACIES

The shape of the accumulative curve gives information about the origin of the deposit investigated, i.e. about the material transported, the manner of differentiation and the mixing of the particles

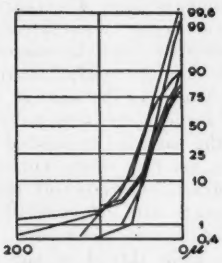

FIG. 29.—Loess deposits (After Udden, De Vries and Doeglas). The straight lines are from samples analyzed by Udden with the microscope.

deposited. In other words, the size frequency distribution of a deposit gives indications on the frequency distribution of the velocities of the current during deposition. One sample, however, provides only data about the conditions at one spot and during a short time interval.

In order to distinguish various sedimentary environments there should be differences in the size frequency distribution of the transported detritus, in the type of differentiation and mixing between these milieus. The type of current in each environment should be different. As variations in the velocity of the current occur in each stream we may expect that the above phenomena of differentiation and mixing will occur in nearly every environment. Regionally, however,

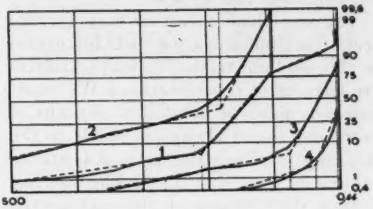

FIG. 30.—Characteristic points of size frequency distributions of sediments.

there will be considerable variations in the distribution of the velocities. The analysis of many samples from a larger area or (vertically) from a layer having a certain thickness will show us the variations of the type of current and the size will give indications of the strength of the currents.

Little is known about the regional distribution of the current velocities in various environments. The main differences will be described below.

The maximum, minimum and average sizes of deposits depend on the strength of the currents. Currents which can transport pebbles and gravel only occur in relatively narrow channels, viz. in rivers, gullies and channels between islands and in some cases along the coast due to wave action. Marine currents are generally too weak to transport grains >2 mm. Coarse deposits which occur e.g. in the Channel and along the northeastern coast of the U.S.A. are actually glacial deposits which have been reworked by marine currents and wave action. Real deposits of coarse detritus therefore are limited to rivers, glaciers, mudflows, fans and beaches. Deposits of

clay only occur at places where the velocity drops to zero, thus in lakes, sheltered places along rivers, estuaria, inland seas, tidal flats, bays and the deep-sea.

Sands need only moderate currents to be transported and they occur in nearly every environment with the exception of large quiet water bodies, e.g. the deep-sea and large lakes.

The size alone therefore may exclude certain surroundings, e.g. pebbles, gravel or clay exclude aeolian deposits. (Eluvia are left out of consideration.) We must, however, keep in mind that detritus of every size is not always available to the stream even when the current is strong enough to transport them. The size frequency distribution of the transported material firstly depends on the sizes of the detritus available along the course of the stream. Generally and especially for fossil sediments we do not know the sizes of the available material. Fortunately we do not need to. The stream differentiates the available detritus along its course. The large blocks and pebbles remain in the source area. The smaller pebbles and gravel lag behind, are trapped in lakes and level areas, due to decreasing capacity. Partly they are crushed during the transport. The clay particles are carried away to quiet places. The main part of the course therefore consists of sands.

In broad lines we find downstream from the source area the following sequence of deposits: pebbles, gravel, sand, silt and clay. This separation along the stream may be called regional differentiation. This regional differentiation is complicated by local phenomena. Regional differentiation takes place in the direction of the current, local differentiation mainly in sections normal to it.

For the determination of the facies we have only to do with the sorting of the, already regionally, differentiated products. Only silt and clay particles may be supplied direct from the source.

The average size frequency distribution of many samples from a certain area or layer will give us an impression of that of the transported material. This frequency distribution may perhaps be already characteristic for a certain environment. The local differentiation of this material and the mixing of the differentiation products will give us further clues for the determination of the type of currents which occur, of their distribution and variations in velocity, in other words, of the characteristics of the environment.

RIVERS

Rivers are bound to their stream-bed. Only during flood is this bed broadened. In a section perpendicular to its course there are strong variations in velocity and in general three main parts can be distinguished, viz. the stream-bed, the natural levees and the flood area.

In the stream-bed itself there are large fluctuations in the capacity of the current due to the friction of the banks and the bottom configuration. The coarsest deposits occur in the main thread of the current where commonly erosion takes place and therefore residual detritus (R) is found. Moreover the coarsest detritus here can be transported. Due to turbulent currents the particles are moved toward the banks, get into slower currents and settle (S-fractions). Towards the banks the maximum size and sometimes even the minimum size decreases. During flood the main thread of the current shifts and parts of the bed are remodeled and detritus of varying size is mixed. The large size range of stream-bed deposits of rivers is caused by these strong variations in velocity and the shifting of the current courses.

During flood the main thread of the current, considerably modified, remains in the stream-bed. Outside the stream-bed the velocity generally is smaller. In valleys with a steep grade the water outside the bed may flow rapidly and secondary channels may develop. The deposits then will be similar to those of the actual bed (R+S-types). In level areas, on the contrary, the capacity diminishes rapidly

in a cross section. The coarsest detritus settles in strips along the main bed and forms the natural levees (S+T-types). Outside the levees the velocity is small and at many places the current ceases and the remaining suspension settles entirely. Here we find three sharply defined current types parallel to each other. Due to heightening of its bed the course of the river shifts continuously and forms a network of levees. The variation in grain size therefore is large even when we observe a cross section of a few miles. The deposits of the stream-bed with its considerable size range (fig. 14) in combination with the fine deposits of the levees (fig. 19) and the characteristic shapes of the curves of many argillaceous deposits as pictured in figures 16 and 24 must enable us to recognize fluviatile deposits when a sufficient number of samples have been analyzed.

LAKES

Sediments from lakes have been little analyzed for size. The bottom of many large lakes in the glaciated areas consists of glacial deposits which are slightly remodeled by the weak currents and the wave action. The size frequency distribution of real lake deposits, however, can be deduced from those of fluviatile clays. Types similar to those of figures 19 and 24 must occur. Only along the shores and on the delta may coarse deposits be present. These will be discussed under marine deltas.

MARINE DELTAS

Marine deltas comprise many environments. River-beds, levees and flood areas occur next to bays, beaches, dunes and coastal shallow water deposits. The data given by Dohm (1936) show that nearly all types of distributions occur in the sediments of the Mississippi delta. Only the river bed type (fig. 14) is wanting. Levee- and shallow sea types (similar to the figs. 19 and 11) predominate.

TIDAL FLATS AND SHALLOW SEAS

On tidal flats the sea water, flooding the area during tide, flows through gullies, inward and then spreads over the entire area. In the gullies sea-sands are found. Along the courses of the gullies inland regional differentiation takes place, the coarse grades remaining behind. On the flats alongside the gullies only the fine grades of the sea-sands can be transported and deposited. During the turn of the tide very fine grades and clay (T-fractions) are being deposited, causing complex deposits on shallow spots in the gullies as well as on the flats. Near the ends of the gullies the currents are so weak that the sea-sands cannot be supplied and only particles of the actual marine suspension are being deposited. Fine T-types are the result. The types given in the figures 11 and 19 predominate on tidal flats.

BEACHES

The mechanical analysis of the Dutch beach sands showed that beach sands have no characteristic size frequency distributions. The shape of the curves and the size depends mainly on the detritus available outside the coast. It is generally accepted that the material on the Dutch Coast is being transported from south to north. The direction of the coastal currents is northward. The minimum size and the median of the beach sands, however, increase from south to north. According to experimental studies of Timmermans (1935) the beach sands are derived from deposits perpendicular to the coast-line and the mechanical analysis confirms this hypothesis. Five groups of curves can be distinguished along the coast, the transitions between subsequent groups being sharp (within one mile). It was proved that these groups are not due to climatic conditions during the collection of the samples, to carbonate content or coast-defence works. The slope of the sea-bottom is rather uniform and the only factors influencing the differences in size frequency distribution may be ascribed to wave action, currents and available detritus. The influence of wave action and currents can be eliminated as

these do not show such sudden changes parallel to the coast. Only the size frequency distribution of the material present outside the coast (probably partly older deposits) and at the coast (younger and older dunes) influence the frequency distribution of the beach sands.

If this material can be reworked entirely by the surf, its original composition will be the same as that of the beach-sands. This is the case for the Dutch beach sands. If only a part of it can be reworked or fine particles can be carried away by the weak coastal currents, a differentiation will take place. In such cases the size frequency distribution of the beach sands will be characteristic for the beach conditions.

NERITIC AND ABYSSAL DEPOSITS

In the main part of the neritic and abyssal seas we find T-fractions; these deposits are predominatingly argillaceous and composed of the last remnants of suspended material. The deposition of this material is only interrupted in places where volcanic ash or aeolian material is supplied. Many submarine volcanoes deposit in their surroundings coarser detritus. Around the deserts enormous quantities of fine dust (loess) may be spread over the bottom of the neighboring seas lowering the clay content of their deposits.

In the coastal belt of the neritic seas a transition from the fine marine deposits to the coastal rocks occurs. Composed types as given in figure 11 will be found. Coastal marine deposits, therefore, may be similar to those of the tidal flats and bays. No coastal, marine sediments have been analyzed with the sedimentation balance. Data from Thoulet, however, show that these transitional types occur along the southern coast of France in belts parallel to the coast.

AEOLIAN DEPOSITS

Regional investigations of aeolian deposits are not available. From the literature, however, it is to be inferred that the size range is small due to the limited capacity of the wind. Aeolian sands, therefore, are well-sorted and have more or less symmetrical frequency distributions. Grains $>500\,\mu$ soon will lag behind and the fine dust is carried away. Clay deposits are wanting. Regionally there will be only small variations in the size frequency distribution and size. The shape of the curves will be similar to those of figure 10. The fine dust settles even in air very slowly and is only deposited when the wind ceases. Clay particles, however, may be transported as sand grains causing a small content of fine material during the analysis. The curves get an extension, a tail, at the fine end.

Fine dust is present nearly everywhere in the air during wind. Large masses of fine material may be taken up by dust storms. Then thin layers of dust may be deposited at quiet places. Large transport by wind only occurs in dry areas, and around these enormous quantities of dust may be deposited, forming the loess. The shape of the curves of loess should be similar to the fine T-fractions of figure 26 viz. curve T_8. The lack of argillaceous material, however, modifies this type. The curves (fig. 29) run steep from abt. $80\,\mu$ to $10\,\mu$, then curve to the right and bend to the left at about $2\,\mu$. Above $2\,\mu$ it is slightly curved to the right over its entire length. It is a stretched form of the T-type with a small content ($<20\%$) of particles $<2\,\mu$.

This type is very characteristic for loess deposits. It may, however, occur in beach and coastal deposits of lakes, enclosed bays and along sea-coasts in protected spots. It was found e.g. along the northeast coast of the Zuiderzee during its reclamation. An aeolian origin is precluded here. The areal distribution is small, as distinct from loess deposits, which have a large distribution.

CONCLUSION

The above data show that there is considerable variation in the distribution of

the various types in different sedimentary environments. If sampling is done over a large area or in a thick layer these variations can be found. As yet it is not known what the ratio of the different types of distribution in each area is. Mechanical analyses of a large number of samples from various environments in different parts of the world have to be made in order to fix the average type of size frequency distribution for each of them.

If this is done, it might be found that these differences also can be seen megascopically. Detailed studies on a more regional scale to find the difference in variation of the grain size have never been made. Simultaneous studies of the structure of the formation in each environment could be made. These too will give important data for the distinction of the facies. Geologists have used these phenomena for a long time already. These structural features, however, are still based on rather old studies, mainly made on fossil sedimentary layers. Recent sediments have never been studied in a regional way. The homogeneous size frequency distribution of sediments from deserts, loess formations and the deep-sea are in strong contrast with e.g. fluviatile deposits. Investigations by the Senckenberg Institution of the structure of tidal flat deposits prove that characteristic structures occur. At present we may not generalize these data for tidal flat-structures as they may occur in the coastal belt of open seas and lakes. A simultaneous study of the size frequency distribution and the structure on a regional scale in many sedimentary environments will give important and useful data for the interpretation of the facies of fossil deposits.

Mechanical analyses should be made accurately, determining many grades. The results should be interpreted by means of the arithmetic probability paper. The characteristics of the size frequency distributions show up clearly on this paper.

The size frequency distribution of the fine grades ($<5\ \mu$) of argillaceous sediments also remains an interesting point for further study. So far they have been left out of consideration as the size frequency distribution of the suspended and deposited material $<5\ \mu$ is different from that of the material treated in the laboratory with peptizing agents. In Dutch marine clays the ratio of the weight percentages of the grades $<2\ \mu$ and in many cases even those $<16\ \mu$ is constant (Hissink cited by Zuur). Probably this is due to the homogeneous composition of the suspension in seawater. In fluviatile clays this ratio varies. In the sea the fluviatile suspensions of various sources remain in suspension for a long time and are thoroughly mixed, thus obtaining a great homogeneity.

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